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Spiral structure in the accretion disc of the binary IP Pegasi

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ABSTRACT

We have found the first convincing evidence for spiral structure in the accretion disc of a close binary. The eclipsing dwarf nova binary IP Peg, observed during the end phase of a rise to outburst, shows strong Balmer and Helium emission lines in its spectra, with asymmetric double peaked velocity profiles produced in the accretion disc around the white dwarf. To reveal the two armed spiral on the accretion disc, we de-project the observed emission line profiles onto a Doppler coordinate frame, a technique known as Doppler tomography. The two armed spiral structure we see in the Doppler tomograms is expected to form when the disc becomes sufficiently large in outburst so that the tides induced by the secondary star can excite waves in the outer disc. Such spiral waves have been predicted in studies of tidal effects in discs and are fundamental in understanding the angular momentum budget of accretion discs.

Key words:
accretion,accretion discs – stars:cataclysmic variables – stars:individual:IP Peg – hydrodynamics

1 INTRODUCTION

IP Pegasi is an interacting binary system containing a white dwarf receiving mass through an accretion disc from a Roche lobe filling late type star. These accretion disc fed systems called cataclysmic variables (see Warner (1995) for an excellent overview) provide one of the best laboratories for accretion physics due to their proximity and convenient time scales. The strong emission lines in their spectra originate in the accretion flow and are powerful observational probes of the local gas conditions. The picture of a viscous disc, transporting angular momentum outwards as material slowly spirals inwards, forms the basis of our understanding of accretion flows in X-ray binaries and AGNs as well.

One of the main longstanding problems of accretion discs is their angular momentum transport mechanisms. In order to sustain the observed mass transfer rates highly efficient viscous processes must be available to transport the angular momentum outwards. Although the famous α prescription (Shakura & Sunyaev 1973), which scales the effective viscosity by a dimensionless parameter α, has been very succesfull it also shows how poorly these processes are understood. Turbulent magnetic fields (Tout & Pringle 1992, Schramkowski & Torkelsson 1996) and spiral shocks (Spruit et al. 1987) are two promising mechanisms even though the effective α expected from such models is still low. A second issue that has received less attention is the removal of the angular momentum at the outer disc via a tidal torque between disc and companion star (e.g. Papaloizou & Pringle 1977).

IP Peg is a member of the subclass of CVs called dwarf novae that display semi-periodic outbursts during which the system brightens by several magnitudes as more mass is suddenly transfered through the disc. These systems provide a great test case for accretion disc models. IP Peg is one of the few eclipsing dwarf novae, where the inclination of the orbital plane ($\sim$80°) is large enough for the 0.5 $M_\odot$ companion star to cover the 1.02 $M_\odot$ white dwarf and most of the accretion disc as it passes in front every 3.8 hours. IP Peg's outbursts have an amplitude of about 2 magnitudes and recur roughly every 3 months during which the accretion disc is the dominant light source.

We present spectrophotometric observations of the dwarf nova IP Peg at the late stages of a rise to outburst and use Doppler imaging to map the accretion disc. Observations are presented in section 2 followed by the analysis of the tomograms in section 3. The tidal origin of the spirals is discussed in section 4.

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2 OBSERVATIONS

The data we present here are part of a long term service program to study IP Peg throughout its outburst cycle. Time-resolved CCD spectrophotometry with the 2.5m Isaac Newton Telescope on La Palma was used to study the strong emission lines originating in the accretion disc both during quiescence and outburst. Here we will focus our attention on the data obtained during the night of 19 August, 1993. IP Peg had just gone into outburst a day before and was close to its maximum brightness level. The Intermediate Dispersion Spectrograph was used to obtain spectra between 6300 and 6800 Å, covering Hα and HeI(λ6678) at a mean dispersion of 0.56 Å pixel^{-1} or 38 km s^{-1}pixel^{-1}. A 1024×1024-pixel TEK CCD chip recorded long slit spectra of IP Peg and a comparison star to account for slit-losses. Neon arc spectra were regularly recorded for wavelength calibration and the flux standard BD+28°4211 was used for flux calibration. This setup allowed us to optimally extract spectra with an absolute flux scale. A total of 15 spectra with an exposure time of 360 s where obtained sampling 60% of the 3.8 hour binary orbit.

The top panels of Figure 1 show the Hα and HeI(6678) line profiles as a function of binary phase after subtracting a low order spline fit to the continuum of the individual spectra. Orbital phases were calculated using the Wolf et al. (1993) ephemeris without their quadratic term;

$$T_0(HJD) = 2445615.4156 + 0.15820616E$$

with T_0 corresponding to mid-eclipse. The AB$\sim$12.6 mag continuum increasing by $\sim 7\%$ during the 2 hour observing window, shows that IP Peg was near the top of its rise to outburst, which typically lasts 1–1.5 d.

3 DOPPLER MAPS

To interpret the phase dependent line profiles $f(v, \phi)$ (Fig. 1), we use Doppler tomography (Marsh & Horne 1988), an indirect de-projection technique very similar to CAT scanning used in medical imaging. The Doppler map $I(\mathrm{V}_x,\mathrm{V}_y)$ gives the emission line flux of gas moving with velocity vector $V = (V_x, V_y)$ in the rotating frame of the binary. As the binary rotates, projections of the rotating velocity vector onto the line of sight traces the sinusoidal radial velocity curve;

$$V(\phi) = -V_x \cos\phi + V_y \sin\phi$$

The observed line profiles $f(v, \phi)$ can therefore be modelled as projections of the map $I(\mathrm{V}_x,\mathrm{V}_y)$ without making specific assumptions about the form of the velocity field of the accretion flow (see also Robinson, Marsh & Smak 1993 and Horne 1991). A maximum entropy implementation was used where the Doppler image is built up iteratively. Any given map is projected to produce the predicted line profiles for the particular map. χ^2 statistic is used to determine goodness of fit while the entropy is maximised to select the simplest image that can fit the data to the required χ^2 value.

This technique assumes that the disc pattern is constant throughout the data set (in the co-rotating frame of the binary) so that the line variations can be modeled by projection effects. Transient features will therefore be averaged out over the map so that the average co-rotating pattern is recovered. Tidal distortions co-rotate in the binary frame and therefore do not suffer from this restriction and are ideally recovered by Doppler tomography. A second problem can be secular variability of the system within the data set used for tomography. In our case the continuum showed little increase during the course of our observations (i.e. outburst was developed) and as our observations cover only $\sim$ 2h, which is sufficient to calculate a Doppler image as more than half of the orbital period is covered, secular changes were negligible. Furthermore, line flux variations were compatible with the changing contribution of the companion star as the illuminated inner face comes into view, while the disc contribution was stable.

Middle panels of Figure 1 show the two maps constructed from the observed Hα and HeI(6678) line flux. As a comparison, bottom panels show predicted data and can be used to check how well the Doppler image reproduces the observed line emission. The gas stream trajectory and position of the companion star's Roche lobe is plotted based on the known system parameters (Marsh & Horne 1990). Strong secondary star emission (K_2=300 km s^{-1}) is visible in both lines, a common feature of dwarf novae in outburst and is thought to be due to irradiation of the inner face of the star. However, emission from the companion has also been observed during quiescence (Harlaftis et al. 1994) and can be related to intrinsic activity of the late type star as the secondary star is co-rotating in a binary with a period of only several hours. There is also a weak low velocity component in the Hα image, which was observed a week later by Steeghs et. al (1996) who propose prominence like structures to be responsible for this feature. This emission is thus already present early in outburst, even though it is more pronounced a week later.

Disc emission is centered on the white dwarf (K_1=147 km s^{-1}) and has a strong azimuthal asymmetry in the form of a two armed spiral pattern. Both lines show similar structure but the arms are more sharply defined in the HeI map. The line flux in these spirals is about a factor of $\sim$4 stronger than that of the disc emission outside the spirals pointing to considerable heating and density enhancement. The velocities of the disc material in the two arms decrease from $\sim$700 km s^{-1} down to $\sim$500 km s^{-1} with increasing azimuth, suggesting a highly non Keplerian flow. A Keplerian accretion disc on the other hand would produce circular rings of emission, each velocity corresponding to a particular Kepler radius ($V(r) = \sqrt{GM/r}$) as has been observed in tomographic studies of other binaries. Note that the two arms are not perfectly symmetric, the arm in the upper right of the tomogram is slightly stronger.

4 TIDES IN THE OUTER DISC

The presence of the companion star will perturb the disc material from their circular Keplerian orbits in the outer disc, ultimately resulting in intersecting orbits outside the radius referred to as the tidal radius (Paczynski 1977). For IP Peg this occurs at $\sim$0.7 R_{L_1} and is thought to represent the maximum radius of a quiescent disc. This tidal interaction is essential in extracting the angular momentum, transported outwards through the disc by viscous processes, from the disc via a tidal torque. Hydrodynamic simulations

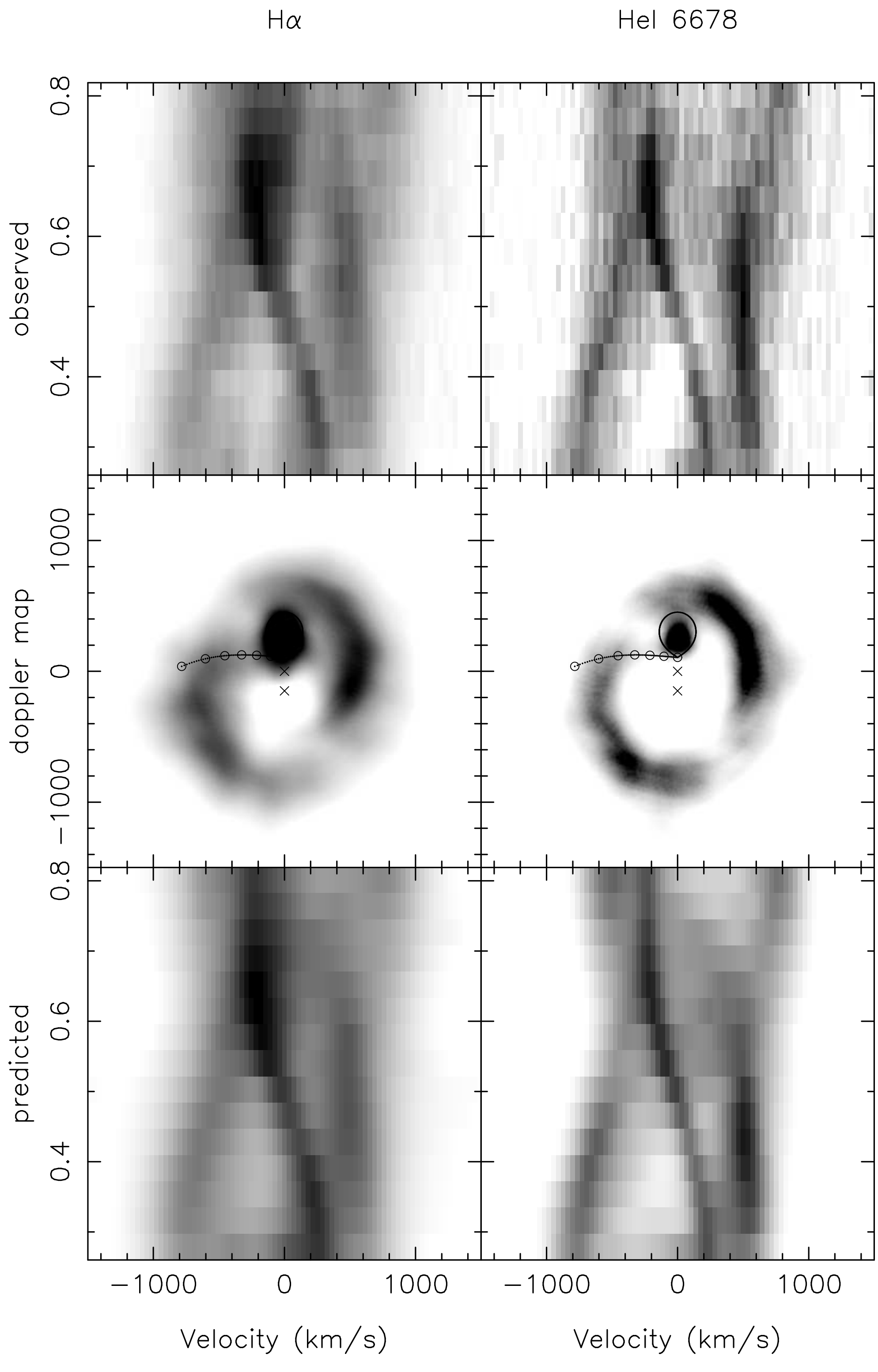

Figure 1. Top panels show the observed line flux from IP Peg as a function of binary phase with Hα on the left, HeI(6678) on the right. Middle panels are constructed Doppler tomograms with theoretical gas stream and Roche lobe plotted for comparison. Bottom cross denotes white dwarf, middle cross the system center of mass at V=(0,0). Bottom panels show predicted data constructed by projecting the Doppler image at the observed phases used to determine how well the image fits our data.

(Sawada et al. 1986, Savonije et al. 1994, Heemskerk 1994) and analytical work (Spruit et al. 1987, Dgani et al. 1992) on this tidal interaction show that spiral waves, and even shocks, are expected to be generated in the accretion disc down to quite small radii, depending on the Mach number of the disc flow. For hot accretion discs (low Mach numbers), these trailing waves can provide a steady mass transfer rate by transporting angular momentum outwards without the need of intrinsic disc viscosity. For the high Mach numbers expected in CV discs, the effective α is low, however ($\leq$ 0.01), and is therefore likely not the dominant transport mechanism in the inner disc, but will still dominate the dynamics of the outer disc.

Many Doppler maps have previously been constructed from observations of discs, but those have never shown obvious evidence for the spiral waves predicted by theory. Our observations now for the first time provide observational evidence for a two armed trailing spiral in a dwarf novae disc. To confirm whether a two armed spiral can indeed produce the observed line profiles, we constructed a Doppler map of a model disc containing two symmetric trailing spiral arms, as shown in Figure 2. This model assumes a two-armed trailing spiral pattern in the spatial line emissivity of the disc, covering the outer part of the disc between 0.4 and 0.9 R_{L_1} (Figure 2, bottom). The velocity coordinates conserve its azimuthal shape, resulting in a model Doppler image with two spirals as well (Figure 2, middle panel). Note that the model was optimised to reproduce the velocities of the observed spirals. The arms span $\sim 110^{\circ}$ in azimuth, and appear to be very open. The quoted radii corresponding to this are the Kepler orbits that limit the spirals. The predicted line profiles of this model are shown in the top panel and demonstrates a close resemblance to the observed data of Figure 1. The key signature is the modulation of the double peak separation. The two peaks measure the radial velocity of material on either side of the disc moving almost directly towards and away from the observer. Their separation would be constant as a function of binary phase for an axisymmetric (Keplerian) disc for example. Note also the jump in velocity around phase 0.7 where one crosses from one arm to the other. While general asymmetries in the local emissivity can be produced by non circular orbits, the fact that it has the shape of a spiral strongly favors the interpretation that we are indeed seeing a spiral density wave in the outer disc. As the orbits start to intersect pressure and viscous forces will setup density waves and possibly even shocks.

Tomography of the final stages of the outburst, about a week after our data (Steeghs et al. 1996), reveals a similar asymmetry pattern in the disc, most obviously in HeI. The much stronger companion star emission dominates over the disc emission and the fainter disc structure suggests the disc is shrinking and the tidal distortions are damping out.

Simulations suggest large, hot discs are needed to generate strong waves (Savonije et al. 1994). Dwarf novae discs are considerably larger and hotter during outburst than in quiescence (e.g. Ichikawa & Osaki 1992, Wood et al. 1989) due to their high mass accretion rate state. Tidal forces will therefore be similarly enhanced. A combination of those two factors (temperature and size) would explain why quiescent discs do not seem to show such structure while (early) outburst discs do. Doppler mapping studies of dwarf novae in the early phase of outburst on several consecutive days, may be able to record the dynamical behaviour of the spiral waves.

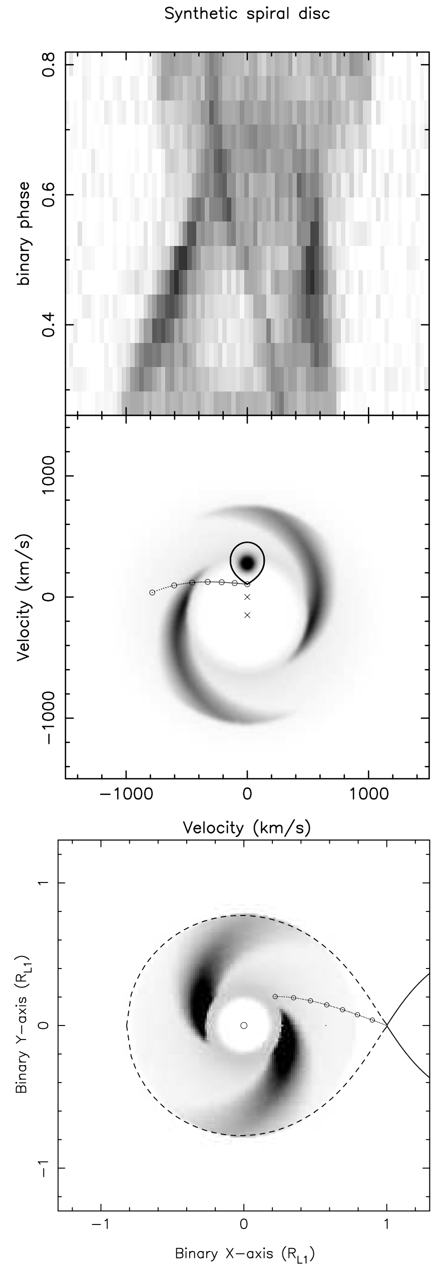

Figure 2. A model Doppler tomogram containing a two armed trailing spiral superposed on symmetric disc emission. A Gaussian spot at the secondary is added to simulate its contribution to the data.Top panel shows the predicted data from such a system with the same signal to noise as our observations (compare with top panels of Figure 1). Middle panel is the model tomogram and bottom panel shows a spatial image of the disc emissivity pattern.

The very start of the outburst is were the two competing models for the outburst, a disc instability (DI) on one hand (Osaki 1974) or a mass transfer burst (MTI) (Bath 1985) on the other, predict different disc behaviour. In the MTI model, the sudden addition of low angular momentum gas causes the disc to shrink initially before it grows again through viscous forces. In the DI model, the disc expands as soon as it switches to the high viscosity state at the on-

set of the outburst (e.g. Ichikawa & Osaki 1992). Our data suggests a large (almost filling the full Roche lobe), non Keplerian accretion disc, possibly exceeding its tidal radius, is present very early on in the outburst, and therefore favors a DI as the trigger of the outburst.

5 SUMMARY

The tidal interaction manifestated in the spiral pattern turns out to be an important factor for outburst discs. Work is now in progress to use different observations of this phenomenon in different emission lines and at different epochs to sample the physical conditions of the disc material. Observing high ionization lines like HeII can show the presence of shocks and will indicate the implication for the angular momentum budget. Furthermore future observations of disc structure in different objects (with different mass ratios and disc sizes) will provide us with a new insight in tidal theory and perhaps the outburst mechanism. In this way dwarf novae disc provide an excellent laboratory for tides in astrophysical discs, since the time scales of the outbursts lasting a week and recurring every couple of months, allows one to study the dynamical behaviour of the disc and its tidal response. Tidal spirals in galaxies for example, thought to be generated in the same manner by a companion galaxy, have very long dynamical time scales making it impossible to study their evolution.

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